Stormwater Action Monitoring - Effectiveness Studies

Modeling Study Plan - DRAFT

Evaluation of Hydraulic Control Approaches for Bioretention Systems

Prepared for review by the Project Technical Advisory Committee

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1 Introduction and Background

The Evaluation of Hydraulic Control Approaches for Bioretention Systems Study (the Study) is intended to compare the side-by-side pollutant removal and hydraulic performance of media treatment flow through rate controlled bioretention mesocosms to outlet-controlled bioretention mesocosms. Fourteen existing mesocosms at the Washington State University (WSU) LID Research facility in Puyallup, Washington were configured to represent bioretention cells with various filtration media and outlet control configurations. In accordance with the Quality Assurance Project Plan (QAPP) (Geosyntec & WSU, 2020) the study design included continuous hydraulic monitoring, six water quality sampling events, and three special hydraulic monitoring events. Testing was mostly completed between January 2021 and June 2022. An additional special testing event was conducted in August 2022 to fill data gaps. This study is a collaboration between WSU and Geosyntec Consultants (the research team).

As described in the QAPP, the research team will conduct a modeling study to extend the mesocosm monitoring results to assess the potential impacts of hydraulic control approaches on idealized case studies in Western Washington. The purpose of the modeling study is to evaluate three aspects of bioretention performance that could not be fully evaluated in the mesocosm study. The following questions would be addressed:

1. How would the use of outlet control versus media control influence long term capture efficiency? The mesocosm study was relatively short and had limited ability to adjust the ratio of drainage area to mesocosm area. Monitoring data from the mesocosms do not describe long term capture efficiency of systems designed per applicable sizing guidance from the Stormwater Management Manual for Western Washington (SWMMWW).
2. How would the use of outlet control versus media control influence long term volume reduction in cases where soils below actual systems allow some infiltration? The mesocosms are fully lined, so this aspect was not studied.
3. How would the use of outlet control versus media control influence long term flow control to reduce downstream erosion? The study was too short to develop an estimate of long term flow control benefits across a representative range of storm events and sizing factors.

We are also interested in understanding how well the Western Washington Hydrology Model (WWHM) representation of bioretention hydraulics aligns with what was observed in the mesocosms.

The research team will approach these questions in four steps, which are explained in detail in this chapters below:

- **Step 1: Develop stage-storage-discharge (SSD) relationships from mesocosm monitoring data.** Using various hydraulic monitoring data from the mesocosm study, we will develop SSD curves for each mesocosms where the field monitoring data supports this. These SSD curves will be compared to the SSD curves for equivalent systems as produced by WWHM so assess similarity. The SSD curves are one primary way in which mesocosm data will be incorporated into the modeling study.

- **Step 2: Develop and run idealized scenarios in WWHM.** The research team will develop models representing idealized scenarios of bioretention with underdrains with different media types, hydraulic control approaches, underlying soils (infiltration rates), and sizing criteria. In total, sixteen idealized scenarios will be developed, as detailed in this study plan.
- **Step 3: Compare model results.** We will extract model output and summary reports from WWHM to assess the following metrics for both media- and outlet-controlled systems:
  a. Long term (40-year) capture efficiency of runoff
  b. Long term (40-year) volume reduction, and
  c. Flow control benefits
- **Step 4: Evaluate net pollutant removal differences.** We will combine capture efficiency and volume reduction results with water quality monitoring results to estimate the total net impact of media and outlet controls on pollutant loading for different scenarios.

2 Availability and Reliability of Monitoring Data for Modeling Study

This section summarizes the monitoring data that are available to use in this modeling study and includes our assessment of the most relevant and reliable monitoring data to support the modeling study. Note that not all of the data collected as part of the mesocosm study will be used in this modeling study; separate analyses of monitoring data will be reported and analyzed in Task 5 beyond what are used in this modeling study. Summary of Monitoring Data Available for Modeling Study

2.1 Summary of Experiment Design

The experiment design for this research was documented in detailed in the Quality Assurance Project Plan (Geosyntec, 2020). The experiment was designed to compare the water quality and hydrologic performance of bioretention mesocosms with and without outlet controls and focused on mesocosms completed with the standard Washington State BSM blend of 60% sand and 40% compost by volume (“standard 60/40 BSM”). The study monitored the performance of six mature mesocosms, six newly retrofitted mesocosms containing the standard 60/40 BSM, and two newly retrofitted mesocosms containing an alternative BSM (fourteen in total). An overview of the experimental design is presented in Table 1.

Table 1. Study design overview

Type	BSM Design Description	Media Control	Outlet Control	Research Comparison
Mature Mesocosms	Mature Standard BSM (sand / compost) with mature plants	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	Effect of outlet control on performance of aged standard BSM with mature plants.
Newly Retrofitted Mesocosms	Standard BSM (sand / compost) with new plants	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	Effect of outlet control on newly retrofitted standard BSM mixes.
Newly Retrofitted Mesocosms	Alternative BSM mix with new plants	1 replicate with full instrumentation and WQ sampling	1 replicate with full instrumentation and WQ sampling	Effect of outlet control on newly retrofitted alternative BSM mixes.

1 – All replicates will be monitored for hydraulics, vegetation, and maintenance.
2 – A subset of replicates will be monitored for water quality, soil moisture, and conductivity monitoring.

2.2 Summary of Monitoring Data Available for Modeling Study

The installation activities for retrofitting the fourteen mesocosms at WSU's research facility were completed on January 7th, 2021 (Installation and Start-up Report, March 2021). Following the completion of the retrofit, continuous precipitation and hydraulic monitoring began on January 8th, 2021 and lasted till June 30th, 2022. This period of record will be referred to as "monitoring period" in this plan. During the monitoring period, the inflow, outflow, surface ponding and bypass occurrences at all fourteen mesocosms were measured and recorded at a 5-mintue interval.

Six of the fourteen mesocosms were equipped with soil moisture content meters. Continuous soil moisture content monitoring was also conducted at these six fully instrumented mesocosms throughout the monitoring period at 5-minute interval. In addition, influent and effluent samples were collected at these six mesocosms during six water quality monitoring events; in-situ hydraulic conductivity and residence time testing were also conducted in three special testing events at these six mesocosms. The testing procedures for these discrete monitoring events are documented in the QAPP. The timeline of these monitoring events are summarized in Table 2 and all of the field data collected which will be used for the modeling study are summarized in Table 3.

Table 2. Discrete Monitoring Events Timeline

Monitoring Event ID	Water Quality Monitoring Event	Special Testing Event
1	2/17/2021	2/18/2021
2	4/21/2021	
3	10/25/2021	10/27/2021
4	12/8/2021	
5	4/6/2022	4/7/2022
6	5/17/2022	
7 (extra)[1]		8/26/2022, 9/1/2022

1 – Two additional drawdown tests were performed to estimate the in-situ stage-storage-discharge relationship for the three fully instrumented mesocosms with outlet control. See details in Section 2.2.5.

Table 3. Summary of Data Collected for this Modeling Study.

Monitoring Type	**Monitoring Period**	**Mesocosms**	**Description of Data**
Precipitation	January 2020 – June 2022 5-minute recording interval	N/A	Continuous monitoring of precipitation using an on-site weather station at WSU
Continuous Hydraulic Monitoring	January 2020 – June 2022 5-minute recording interval	All fourteen mesocosms	Continuous monitoring of inlet flow, outlet flow, surface ponding depth and overflow
Water Quality Sampling	6 water quality monitoring events	Six fully instrumented mesocosms	Periodic composite water quality sampling during six synthetic storm events within the monitoring period
Soil Moisture Monitoring	January 2021 – June 2022 5-minute recording interval	Six fully instrumented mesocosms	Continuous soil moisture monitoring
In-Situ Hydraulic Conductivity Monitoring	3 special testing events	Six fully instrumented mesocosms	Inflow, outflow, ponding and soil moisture content data.
Additional Ponding/ Drawdown Tests	1 additional event	Three fully instrumented mesocosms with outlet control	The research team performed 2 additional drawdown tests with outlet control devices in place in August 2022 to help fill data gaps for the modeling study.

In January 2022, one year after the monitoring period started, the research team reviewed the continuous monitoring data collected in the 12-month period. During the review process, the research team identified that original tributary area to the mesocosms from the QAPP was insufficient to induce ponding during majority of the precipitation events occurred in 2021. As a result, the research team decided to divert all of the runoff (instead of 25% originally proposed) from the tributary area to the fourteen mesocosms on February 15, 2022. This change resulted in observed ponding in most of the mesocosms from February 2022 to the end of the monitoring period (June 2022).

Bromide tracer testing, vegetation monitoring, operations and maintenance monitoring were also conducted throughout the monitoring period but excluded from this data summary because these data are not intended to be used this modeling study.

2.3 Assessment of Data Reliability for Modeling Study

In the process of preparing this study plan, we reviewed the monitoring datasets inventoried in Table 3 to determine the subset of data that are reliable and readily usable for this modeling study. This involved quality control (QC) checks, as well as assessment of which datasets most directly support the needs of the modeling study.

2.3.1 Precipitation Data

Precipitation has limited value of the modeling study. The timing of rainfall is not important to developing SSD curves. Additionally, for the modeling study, a long-term precipitation record with at least 40 years of period of record from WWHM will be used.

2.3.2 Continuous Flow Monitoring Data

Quality control checks were conducted for the flow measurement data of the influent to and effluent from the mesocosms. The first QC task conducted was comparing the total volume of effluent from each mesocosm and the total volume of influent throughout the entire monitoring period. This comparison was intended to ensure that the total volume of outflow from each mesocosm is approximately the same as the sum of inflow volume and estimated evapotranspiration. It should be noted that there is only one inflow measurement at the flow distribution cistern and the total flow to each mesocosm vary slightly due to the small difference in the invert elevation of the V-notch weirs which convey flow from the flow-distribution cistern to the mesocosms.

During this water balance check, we found that the effluent volume from all but one mesocosm are within 70% to 105% of the inflow volume, which is a reasonable range given the slightly uneven inflow and evapotranspiration loss in the mesocosms. At Mesocosm (MC) 23, the outflow volume recorded was 30% of the inflow. The research team performed an inspection at the mesocosm and found that the taproot of the dogwood planted in MC 23 was found to have protruded from the outlet structure of the mesocosm, resulting in outflow from the mesocosm bypassing the flow meter for the entirety of the monitoring period after the inflow increase. Due to the uncertainty in when this incident occurred, the flow recorded at this mesocosm will not be used for analysis.

The continuous monitoring data for the period after the study adjustment in February 2022 (increase in tributary area) are most valuable for the modeling study. During this period, ponding occurred more often. Isolating larger storms within this period is one line of evidence to estimate SSD relationships. However, the media-controlled mesocosms still did not pond significantly in this period.

2.3.3 Continuous Ponding Data

The pressure transducer (PT) measurements at each of the fourteen MCs were converted to ponding depth by subtracting the depth of water column above the PT from the distance from the media surface to the bottom of the PT. After the conversion, temporal gaps with no measurement recorded were documented and excluded from the analysis. Outlier values were identified and replaced using interpolation or eliminated from the analysis. After these QC steps, continuous 5-mintue ponding time series were produced for the modeling and data analysis in this study.

Ponding measurements serve an important role in developing SSD curves; however, they only describe the water level when it is above the soil. So, they are useful for a portion of the SSD curve development.

2.3.4 Continuous Moisture Content Data

Moisture content was measured at one horizon in the media bed for six of the mesocosms. Temporal gaps with no measurement recorded were documented and excluded from the analysis. Outlier values were identified and replaced using interpolation or eliminated from the analysis. After these QC steps, continuous 5-mintue moisture content time series were produced for the modeling and data analysis in this study.

Soil moisture data may be used as a secondary line of evidence for when the free water surface within the media bed drops below the measurement point. However, this has relatively limited value in developing an SSD curve.

2.3.5 Data from Special Events

During hydraulic conductivity testing events (Feb 2021, Oct 2021, Apr 2022), the mesocosms were filled, then allowed to drain completely without further inflow. The water level and outflow data from these events provides a well-isolated way to estimate the SSD curve of media-controlled mesocosms. These tests also provide a direct estimate of the hydraulic conductivity of the media in each cell, which can be used to parameterize the WWHM model.

The outlet control devices were removed from the outlet controlled mesocosms during these tests, so this does not represent the SSD of the outlet-controlled columns. However, to fill this data gap, the research team ran an extra testing event in August 2022 where the mesocosms were filled and drained with outlet control devices in place.

The data from these tests are among the most useful for the modeling study as they isolate the drawdown period without further inflow into the system. These data are available for the chosen subset of the mesocosms.

3 Stage-Storage-Discharge Relationship Analysis

In the modeling study, the hydraulic properties of a bioretention cell with underdrain will be represented by its SSD relationship. The SSD relationship is influenced by the hydraulic properties of the media and the presence of orifice outlet control.

The fourteen mesocosms will be divided into six groups based on media type, age of media, and the presence of outlet control. An SSD relationship will be developed for each group of mesocosms based on the monitoring data summarized in Section 2. The research team will also develop SSD curves in WWHM to attempt to represent the same systems.

3.1 Stage-Storage-Discharge Relationship based on Monitoring Data

For each group of mesocosms, three types of monitoring data will be used to estimate the SSD relationship for each group of mesocosms:

1. Ponding and discharge data obtained as part of the three hydraulic conductivity testing events (Feb 2021, Oct 2021, Apr 2022)
2. Ponding and discharge data obtained as part of the additional ponding/drawdown event (Aug 2022)
3. Ponding and discharge data for selected real storms that induced ponding (subset of cells, after February 15, 2022). This will be used only to corroborate that the SSD curves derived from the datasets above align with what is observed in operation during real storm events.

Different combinations of data are available for different mesocosms. Table 4 summarizes the SSD estimation methods for mesocosms in each mesocosm group.

Table 4. Stage-Storage-Discharge Relationship Estimate for Each Group of Mesocosms

Group ID	Media	Media Age	Effluent Control	Mesocosm IDs	Mesocosms with SSD Estimated from Hydraulic Conductivity Special Tests	Mesocosms with SSD Estimated from Additional Ponding/ Drawdown Test	Mesocosms with SSD from Ponding Events used for Verification	Mesocosms with Insufficient Monitoring Data for SSD Estimate
1	Standard[1]	Mature	Media	13,23,25	13		13	23, 25
2	Standard	Mature	Outlet	22,32,35		22	22, 32, 35	
3	Standard	New	Media	24,33,45	33		45	24
4	Standard	New	Outlet	12,41,42		12	12, 41, 42	
5	Alternative[2]	New	Media	34	34			
6	Alternative	New	Outlet	15		15	15	

[1] The standard BSM contains a mixture of sand and compost. Some mesocosms also include water treatment residuals.
[2] The alternative BSM was developed as a low phosphorus BSM and consists of 70% sand, 20% coconut coir pith, and 10% biochar.

3.1.1 Derivation of Stage-Storage-Discharge Estimated from Special Testing Events

For the three fully instrumented mesocosms without outlet control (13, 33, 34), the flow and ponding data during the in-situ hydraulic events will be used to develop the SSD. During the three hydraulic conductivity testing events, water is pumped into the mesocosms to brim full level with the outlet closed. Subsequently, the outlets were open with the drawdown of ponding and the outflow recorded till the mesocosms were drained to the invert elevation of the outlet (24 inches below the media surface).

The total amount of water discharged during the testing will be used as the freely drained volume of the mesocosm. The freely drained porosity of the media will be estimated based on the volume of water that discharges from the system after the water level drops below the media surface. With the freely drained porosity and total volume estimated above, the stage-storage relationship will be established for range of depth above and below the media surface.

When the water surface level in the mesocosm is above the media surface, stage is directly measured by the pressure transducer (ponding depth meter) and the volume above ponding is estimated by multiplying the footprint of the mesocosm by the ponding depth. When the water is percolating through the subsurface media, the volume of water stored in the media will be estimated using a level-pool analysis, which calculates the volume storage at the end of a time step using the following formula:

$$V_{t+1} = V_t - Q_{out}$$

Where V_t is the storage volume at the beginning of a time step;
V_{t+1} is the storage volume at the end of a time step;
Q_{out} is the outflow volume during the time step t

The stage of the mesocosm will be calculated based on the volume calculated above and the stage-storage relationship and the freely-drained porosity estimated by the total amount of water discharged during the testing. Porosity of the media will be assumed to be consistent across the entire depth of the media layer. By correlating the measured stage above media surface, the estimated stage below the media surface and the outflow measurements at each mesocosm, the stage-discharge relationship will be established.

The same method will be used to estimate the SSD for the three fully instrumented mesocosms with outlet control (12, 15, 22), relying only on the additional ponding/drawdown runs performed in August 2022.

3.1.2 Derivation of Stage-Storage-Discharge Estimated from Precipitation Events with Ponding

As discussed in Section 0, several rainfall events occurred between February 2022 and June 2022 that induced ponding in some of the mesocosms. The ponding depth, inflow, and outflow monitoring data during these events can be used to develop the SSD relationship for the mesocosms.

At nine out of the fourteen mesocosms, several rainfall events that caused substantial amount of ponding (greater than 6 inches) were observed. The stage-discharge relationship above the media surface will be established directly based on the ponding and outflow data. When the water level is below the surface of the media, the volume of water stored in the media will be estimated using a level-pool analysis, which calculates the volume storage at the end of a time step using the following formula:

$$V_{t+1} = V_t + Q_{in} - Q_{out}$$

Where V_t is the storage volume at the beginning of a time step;
V_{t+1} is the storage volume at the end of a time step;
Q_{in} is the inflow volume during the time step t
Q_{out} is the outflow volume during the time step t

Note, depending on precision of the inflow estimates, it may not be possible to apply this method when the water level is below the media surface. If this is the case, we will use the findings from the fully instrumented cells in Section 3.1.1 for the potion of the SSD when water is below the media surface.

3.1.3 Summary

For each mesocosm group, the SSD relationship for the fully instrumented mesocosm in the group can be estimated using data from either the special hydraulic conductivity test or the additional drawdown tests. The SSD relationship can also be estimated using the monitoring data during ponding events for some of the mesocosms. Any major difference between SSD estimated using the two different sources of data will be documented in the modeling report. Otherwise, the average of the estimates from the two sources of data (i.e., average discharge estimate for a given stage) will be considered the representative SSD for the mesocosm.

Within each group of mesocosms summarized in Table 4, the average SSD relationship for all mesocosms with the group will be used as the representative SSD for the mesocosm group for subsequent modeling and analysis. Any major difference in SSD relationship among the mesocosms within the same group, such as due to the soil type difference, will be documented in the modeling report.

3.2 Stage-Storage-Discharge Relationship in WWHM

Six bioretention cells will be created and parameterized in WWHM to represent the six fully instrumented mesocosms in this field study. For these models, the media footprint, media depth, freeboard depth, outlet structures and orifice parameters of the modeled bioretention units will be defined to closely represent the mesocosms used in the field study. The model bioretention units will only contain one soil layer to represent the media in the mesocosms. The default biofiltration soil type “SMMWW” will be selected to represent the standard bioretention soil media (BSM) and “sand” will be selected to represent the alternative BSM. These are the closest default soil types. These will be parameterized with a hydraulic conductivity that aligns with the results of the hydraulic conductivity testing. The remaining soil attributes will be initially set to WWHM defaults.

In WWHM, the SSD relationship of a bioretention element is calculated after the element is parameterized without running a simulation. As a result, the SSD relationship will be extracted from the bioretention and compared to the SSD relationship estimated based on the field monitoring data as described in Section 3.1. Findings from this comparison will be documented in the modeling study report.

If the model and observed SSDs for a mesocosm are similar, adjustments to the soil parameters will be made iteratively in WWHM to refine the alignment between the modeled and measured SSDs. The tuning of parameters will be informed by the data sources summarized in Table 5.

Table 5. Data Source for Soil Parameter Adjustments in WWHM.

Soil Parameter in WWHM	Data Source
Porosity	Estimates derived from monitoring data
K Sat: maximum saturated hydraulic conductivity	Hydraulic conductivity testing results
Van Genuchten Equation Constants: n, alpha & lambda	Literature review

If the modeled and observed SSDs are much different, in either SSD shape or magnitude, and cannot be aligned through parameter adjustment, then this will be documented in the study report. An adapted study approach will be taken where the monitored SSD is scaled and input directly into WWHM, as discussed further below.

4 WWHM Model Development

4.1 Model Scenarios

Sixteen idealized model scenarios will be developed for bioretention with underdrains for both Standard BSM and Alternative BSM with and without outlet controls. These scenarios will consider two underlying soil infiltration rates and two sizing approaches.

Underlying soil infiltration rates will include:

- Upper: 0.6 in/hr. According to the Stormwater Management Manual for Western Washington (SWMMWW), in slow draining soils with a factored underlying soil infiltration rate less than 0.3 in/hour, a bioretention BMP with an underdrain may be used (Ecology, 2019). A minimum correction factor of 2 applies. It is reasonable that the actual underlying soil infiltration below a bioretention with underdrain would be double the feasibility limit. As a result, 0.6 in/hour is selected to represent the upper range of underlying soil infiltration rate.
- Lower: 0.1 in/hr. Bioretention with underdrains could be used without any underlying infiltration rate, but this assumption is intended to represent a very low permeability soil instead of no infiltration.

Sizing scenarios will include:

- Bioretention with underdrains designed per the SWMMWW standard assumptions and iteratively sized in WWHM to treat 91% of the annual average runoff from 1-acre of new impervious surface (full sizing).
- Bioretention with underdrains, sized for half the size as above. This is intended to represent a space constrained retrofit example.

The sizing inputs will be the same for all scenarios and will not be adjusted based on actual media permeability, underlying soil infiltration rate, or presence of outlet controls. Sizing will be based on a 0.3 in/hr underlying infiltration rate and the SWMMWW standard 6 inches per hour media treatment rate. The media treatment rate accounts for a safety factor of 2 under the assumption that the bioretention cells are used to treat small parcels according to the SWMMWW. This analysis will not consider the minor differences in sizing that could result from difference in underlying infiltration rate.

In total, sixteen idealized scenarios will be developed (2 media types x 2 outlet control configurations x 2 soil types x 2 sizing approaches). The sixteen scenarios are summarized in Table 6. In addition, a scenario with no bioretention cell will also be developed so that the water quality and flow control benefit of bioretention cells can be quantified.

Table 6. Summary of Modeling Scenarios.

Scenario ID	Media Type	Effluent Control	Native Soil Infiltration Rate, in/hr	Sizing[1]
1	Standard	Media	0.6	Full
2	Standard	Media	0.6	Half
3	Standard	Media	0.1	Full
4	Standard	Media	0.1	Half
5	Standard	Outlet	0.6	Full
6	Standard	Outlet	0.6	Half
7	Standard	Outlet	0.1	Full
8	Standard	Outlet	0.1	Half
9	Alternative	Media	0.6	Full
10	Alternative	Media	0.6	Half
11	Alternative	Media	0.1	Full
12	Alternative	Media	0.1	Half
13	Alternative	Outlet	0.6	Full
14	Alternative	Outlet	0.6	Half
15	Alternative	Outlet	0.1	Full
16	Alternative	Outlet	0.1	Half

[1] Full sizing scenarios are sized to capture and treat 91% of the annual average runoff based on the SWMMWW standard 12 in/hr media treatment rate and 0.3 in/hr underlying infiltration rate; Half sizing scenarios are sized to half of the full-size requirement.

4.2 Model Elements

In all model scenarios, a completely impervious one-acre catchment will be included and parameterized using WWHM defaults. A 40-year precipitation record in Puyallup, WA from a built-in rain gage in WWHM will be used to generate runoff from the catchment. The runoff will be routed directly to the element representing the bioretention cell in the model.

If the research team is able to reasonably match the model and observed SSD relationship (for both the standard and alternative BSM) by tuning the soil parameters in WWHM. The bioretention cell will be modeled using the bioretention element in WWHM. The bioretention element will be parameterized to represent a typical profile of bioretention with underdrain based on the SMWWMM, including 6 inches of freeboard above overflow stage, 9 inches of ponding depth matching the mesocosm dimension in this design experiment, 18 inches of media layer and 12 inches of gravel layer underneath the media layer as shown in Figure 1.

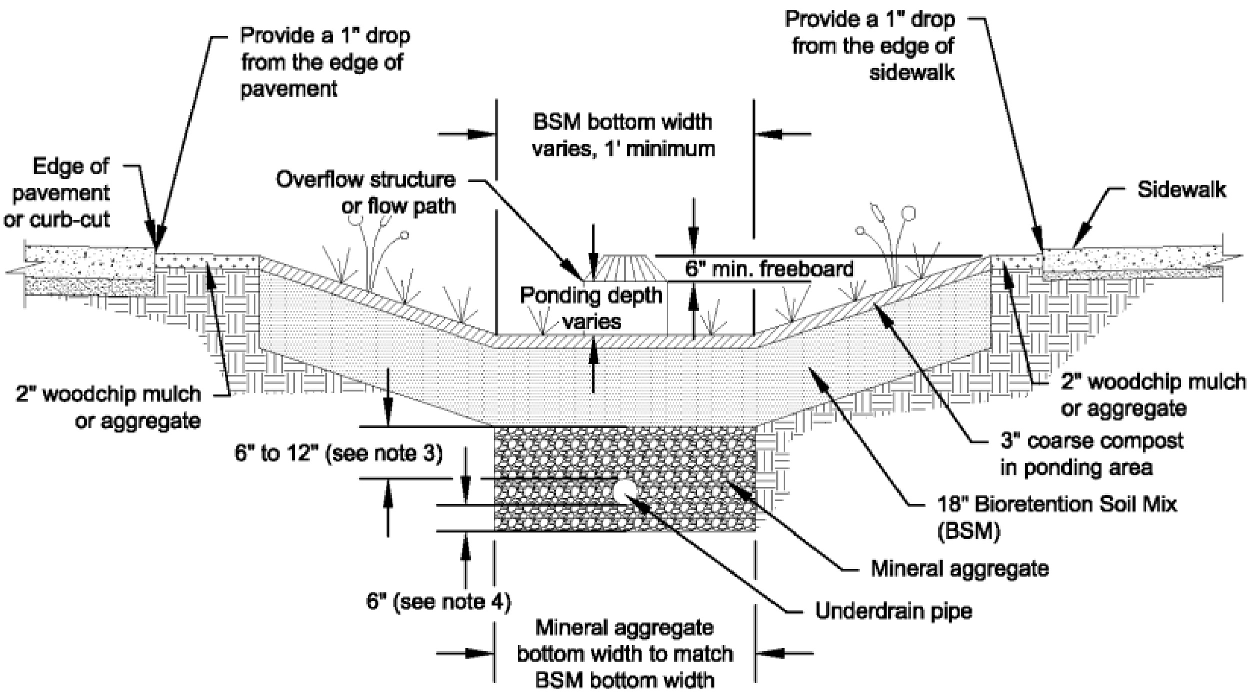

Figure 1. Typical Profile of Bioretention with Underdrain

An underdrain outlet will be placed at 24 inches below the media surface and sized to convey flowrate greater than the hydraulic conductivity of the media when the mesocosm is at brim-full. For the outlet-controlled scenarios, the outlet orifice will be sized to restrict the drawdown rate of the bioretention at brim full level to 6 inches per hour. An overflow outlet will be added to bypass any excess volume above the design 1-foot ponding depth.

The soil layer representing the BSM will be parameterized based on the outcome of the SSD relationship analysis documented in Section 3. For the standard BSM, the SSDs of the mesocosms with mature standard BSM will be used to represent the long-term hydraulic property of the media. The footprint of the bioretention will be based on the sizing analysis discussed above.

If the research team is unable to reconcile the difference between the model and observed SSD relationship by tuning the soil parameters in the analysis documented in Section 3, the bioretention cell will be modeled using an SSD table element in WWHM. The stage-storage relationship of the element will be developed based on the typical profile of bioretention with underdrain as shown in Figure 1 with adequate footprint to capture 91% of the annual average runoff from the 1-acre catchment or half of this footprint based on the sizing scenario. Evaporation will be applied to the SSD element.

Three outlets will be parameterized for the SSD element to represent 1) the overflow outlet 2) the underdrain outlet (with and without the orifice) and 3) the underlying soil infiltration. The stage-discharge relation of the overflow outlet will be calculated using a weir equation. The stage-discharge relation of the underdrain outlet will be from SSD relationship resulting from the analysis documented in Section 3. A constant underlying soil infiltration rate will be assigned to the infiltration outlet of the SSD element, which is consistent with the underlying soil infiltration method built into the WWHM bioretention element.

4.3 Evaluation Metrics

Results from the WWHM long term simulation models for the sixteen idealized scenarios will be extracted and summarized to assess the three hydraulic metrics listed in this section. In the modeling study report, these metrics will be used to compare the long term hydraulic performance difference between bioretention with and without outlet control, and between bioretention with standard and alternative media.

4.3.1 Long Term Capture Efficiency

The long term capture efficiency will be computed using the following equation:

$$Long\ Term\ Capture\ Efficiency = \frac{V_{inflow} - V_{overflow}}{V_{inflow}}$$

V_{inflow} is the total volume of runoff from the 1-acre catchment, the entirety of which flows into the bioretention unit. $V_{overflow}$ is the total volume of overflow that bypasses the treatment from exiting the bioretention cell via the overflow outlet.

4.3.2 Long Term Volume Reduction

The long term volume reduction will be computed using the following equation:

$$V_{reduced} = V_{infiltrated} + V_{evaporated}$$

The long term volume reduction is the sum of the volume exiting the bioretention via infiltration into the underlying soil ($V_{infiltrated}$) and evaporation ($V_{evaporated}$).

4.3.3 Flow Control Benefits

The flow control benefits from the idealized scenarios will be evaluated by comparing the flow-duration curves and the peak flow of 2-year, 5-year, 10-year, 25-year and 50-year return intervals among the scenarios. The flow-duration curves and peak flow tables can be exported directly from the "LID Duration" and "Flow Frequency" analysis modules in WWHM. For the flow duration curves, standard tables will be prepared summarizing the duration at key flows of interest (8% of 2-year, 50% of 2-year, 2-year, 10-year) to provide a numerical comparison. Flow-duration curves will also be provided for the full range of flows within the regulatory ranges associated with LID and stream bank protection criteria.

5 Pollutant Load Reduction Assessment

The modeling results for the idealized scenarios, in combination with the influent-effluent pairing water quality sampling results under this study (Section 2.1), will be used to estimate the pollutant loading reduction for the sixteen scenarios included in this modeling study. The pollutant of interest in this study include total suspended solids, nitrogen (Total Kjeldahl Nitrogen and nitrate-nitrite), phosphorus (total phosphorus and orthophosphate), copper (total and dissolved) and zinc (total and dissolved).

The long term pollutant loading reduction consists of two components: pollutant mass reduced due to runoff volume reduction ($m_{volume\ reduction}$) and mass reduction due to the treatment ($m_{treated}$) occurring at the bioretention unit which leads to lower effluent pollutant concentration compared to the influent. The loading reduction as a percentage of pollutant load in the influent will be computed using the following equation:

$$Pollutant\ Loading\ Reduction\ Percentage = \frac{m_{volume\ reduction} + m_{treated}}{m_{inflow}}$$
$$= \frac{V_{reduced} \times C_{influent} + V_{underdrain} \times (C_{influent} - C_{effluent})}{V_{inflow} \times C_{influent}}$$

The geometric mean of influent and effluent concentration of each monitored pollutant in each mesocosm group based on outlet/media control and media type will be used as the representative influent and effluent pollutant concentration ($C_{influent}$ and $C_{effluent}$) in the equation.

The pollutant loading reduction percentage calculated the will be compared and the differences among sixteen idealized scenarios will be summarized in the modeling study report.

6 References

Clear Creek Solutions, Inc, 2016. Western Washington Hydrology Model 2012 User Manual

Ecology, 2019. Stormwater Management Manual for Western Washington

Geosyntec & WSU, 2020. Quality Assurance Project Plan (QAPP) for Evaluation of Hydraulic Control Approaches for Bioretention Systems.

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